High-Throughput Laser Peening of Metals Using a High-Average-Power Nd:Glass Laser System

C. B. Dane, L. A. Hackel, J. Halpin, J. Daly, J. Harrisson, F. Harris

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DISCLAIMER

High-throughput laser peening of metals
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C. Brent Dane[*a], Lloyd A. Hackel[a], John M. Halpin[a], James Daly[b], James Harrisson[b], Fritz Harris[b]

[a]Lawrence Livermore National Laboratory, Livermore, CA 94550
[b]Metal Improvement Corporation, Paramus, NJ 07652

ABSTRACT

Laser shot peening, a surface treatment for metals, is known to induce residual compressive stresses to depths of over 1mm providing improved component resistance to various forms of failure. Recent information also suggests that thermal relaxation of the laser induced stress is significantly less than that experienced by other forms of surface stressing that involve significantly higher levels of cold work. We have developed a unique solid state laser technology employing Nd:glass amplifier slabs and SBS phase conjugation that enables this process to move into high throughput production processing.

Keywords: Laser peening, shock compression, residual stress, stress corrosion cracking, laser-induced plasma

1. INTRODUCTION

Various forms of cold working have been used by industry for many years to induce beneficial compressive stresses in metals. These include fillet rolling, cold expansion of holes, shot peening and the newest form, laser shot peening. The significant increase in resistance to fatigue, fretting, galling and stress corrosion are well known. Shot peening has been the process most widely used because of its ability to induce these stresses efficiently and inexpensively on parts of complex geometry. The depth of the compressive stress produced by shot peening is limited by the kinetic energy transmitted by the force of the shot and the indention of the surface. Induced stress can reach depths of 0.75mm but the process may leave an undesirable surface finish.

Laser shot peening employs laser-induced shocks to create deep compressive residual stress to depths of over 1mm and with magnitude comparable to shot peening. Laser peening is a more damage tolerant process that has generated sufficiently impressive results that there is keen interest to move it from a laboratory demonstration phase into a significant industrial process. However, until now this evolution has been slowed because a laser system meeting the output pulse energies and average power requirements for a high throughput process has been lacking.

A laser system appropriate for peening at an industrial level requires an average power in the multi-hundred watt to kilowatt range, a pulse energy of around 100J and a pulse duration of 10-30ns. Pulsed lasers with output energies exceeding 10J have historically been limited to low repetition rate and consequently, low average output power. The large fusion lasers such as Lawrence Livermore's Nova laser and the University of Rochester's Omega laser can produce single pulse energies at 1μm wavelength in the 100kJ range but are limited to firing about once every two hours for an equivalent average output power of only tens of watts. Commercially available lasers with pulsed outputs of 10 to 100J, if available at all, are limited to repetition rates of around 0.25Hz resulting in an average power of only 25W. In this paper we report on a highly developed laser technology employing Nd:glass slabs and a master oscillator/power amplifier with wavefront correction provided by SBS phase conjugation. For the first time this technology pushes large pulse energy average power output into the 500W to 1kW range and can meet the requirements of the industrial laser peening process. Figure 1 shows the 100J/pulse, 600W system developed by LLNL and planned for use in the Metal Improvement Corporation (MIC) Lasershot[sm] Peening system.
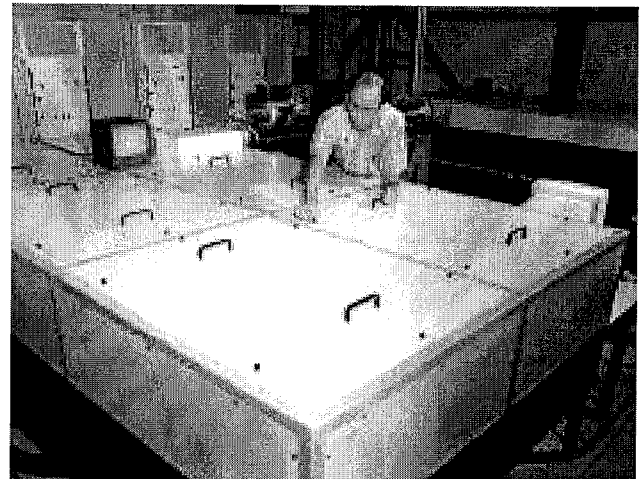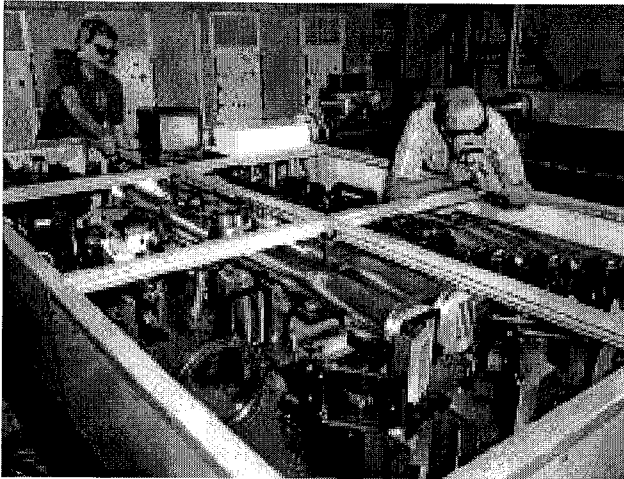
Figure 1. The Nd:glass laser system is a robust, reliable, and fully engineered laser system. Internally, the laser includes advanced technologies such as zig-zag slab amplifiers, passive optical switching with large aperture Faraday rotators, and multi-aperture phase-locking using SBS phase conjugation. This laser, in its long pulse (600ns) version, was designed and constructed for the Air Force Research Laboratory.

2. LASER SHOCK PEENING

2.1. Background

With the invention of the laser, it was rapidly recognized that the intense shocks required for peening could be achieved by means of tamped plasmas generated at metal surfaces with high energy density (~200J/cm^2) lasers having pulse lengths in the tens of nanoseconds range. Initial studies on laser shock processing of materials were done at the Battelle Institute (Columbus, OH) from about 1968 to 1981.[1,2] Excellent recent work has also been reported in France.[3] Figure 2 shows a typical setup for laser peening. Laser intensities of 100 J/cm^2 to 300J/cm^2 with a pulse duration of about 30ns can generate shock pressures of 10^4 to 10^5 atmospheres when absorbed on a metal surface and inertially confined with a surface layer (tamp) such as water. A thin layer of black paint on the surface provides an excellent absorber. These shocks have been shown to impart compressive stresses deeper than those achievable with standard shot peening. Special techniques for controlling the temporal and spatial pulse shape are used to prevent the high intensity laser from breaking down the water column or generating stimulated scattering processes which reflect the laser energy before reaching the painted surface.

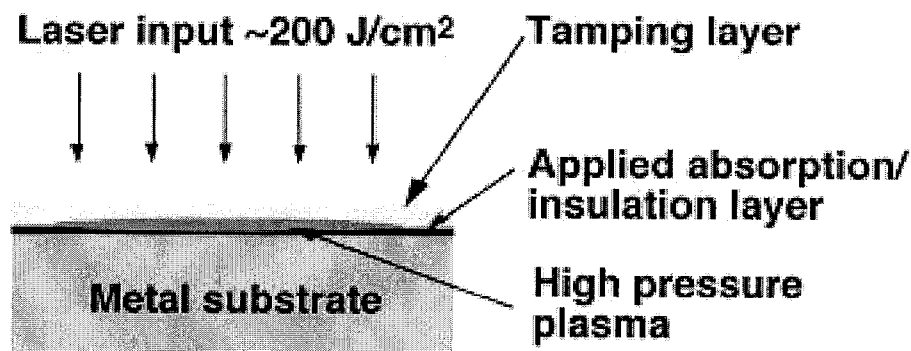**Figure 2.** Typical setup for laser peening including an input laser beam of 200J/cm^2 and 30ns pulse length. The metal layer is covered with a layer of paint to provide light absorption and is covered with a thin water tamping layer to contain the shock.

2.2. Laser^{sm} Shot Peening Measurement Results

As an example of the laser process, Figure 3 shows the residual stress induced in Inconel alloy by laser peening and contrasts it with typical results achieved by shot peening. Clearly the laser-generated shock can be tailored to penetrate deeper into the material and create a significantly greater stress volume. The induced residual stress prevents treated parts from developing cracks due to stress corrosion. Additionally, other types of corrosion will require longer periods of time to penetrate the compression layer induced by Lasershot^{sm} Peening. Deep residual stress is important for critical areas of components such as turbine blades because it prevents debris damage from penetrating through the compressed layer. Foreign object debris (FOD) picked up in operation can often generate damage sites which can breach a thin stressed layer and hence become an initiation point for fatigue cracks.
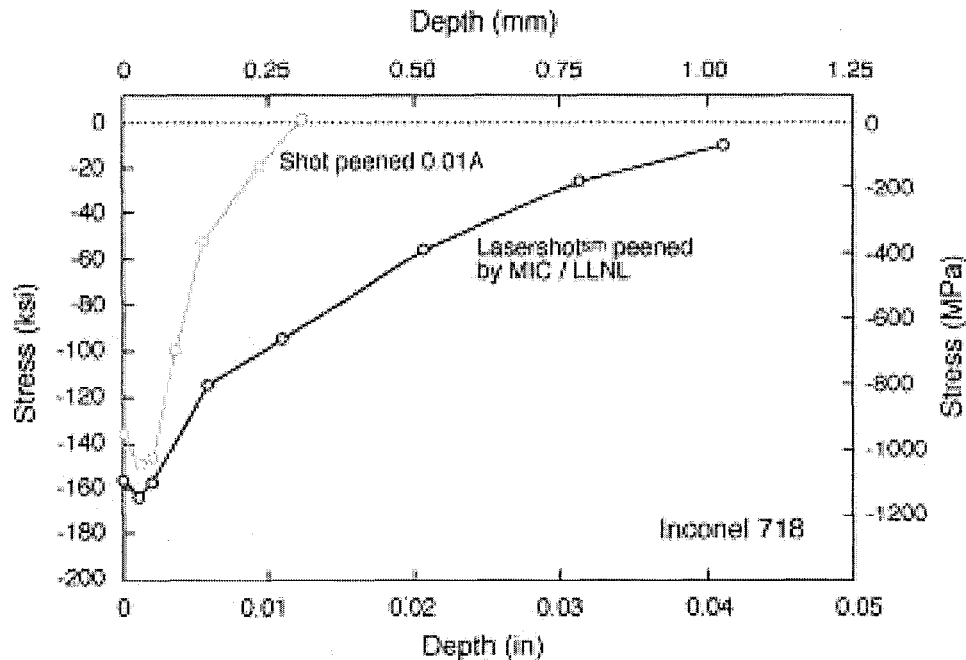

Figure 3. Residual stress induced by laser peening can be made deeper and with significantly greater stressed volume than conventional shot peening. The shot peening was done on an Almen A strip to a deflection of 0.25mm. The Lasershot^{sm} Peening was done with two pulses.

Another important element in obtaining deep residual stresses is the use of successive shocks to drive the stress deeper while not exceeding material limits at the surface. Figure 4 shows results of successive applications to a titanium alloy surface (Ti-6Al-4V) of laser pulses at 200J/cm^2 and a pulse duration of 30ns. As can be seen, the application of a first and then a second shock successively drives stress deeper into the material.

Most metals can be successfully laser shot peened. Figure 5 and 6 show other important aerospace materials peened by the laser process. Both show excellent deep depth of compressive stress. In recently reported work by P. Prevey, et al.[4] of Lambda Research, a detailed study was done of thermal relaxation of the layer of compression induced by shot peening, gravity peening and laser shocking in Ti-6Al-4V and Inconel 718 at temperatures of 230C to 425C. For shot and gravity peening, the repeated dimpling of the surface results in a highly cold worked layer. Conventional shot peening produces from 10% to 50% cold work. Gravity peening utilizes fewer impacts with larger shot, producing a less cold work in the surface layer. The laser process produces remarkably little cold working of the surface (1 to 2%) because only a single or a few deformation cycles are required. The authors find that the initial thermal relaxation of highly cold worked surfaces can be far more rapid than previously realized and can result in 50% loss of residual stress after 10 minutes at temperature. However, the laser process which produces minimal cold working of the surface has exhibited striking resistance to thermal relaxation. No detectable relaxation was produced in the tests at the lower temperature and, at the highest temperature of 425C, only a small loss occurred near the surface.
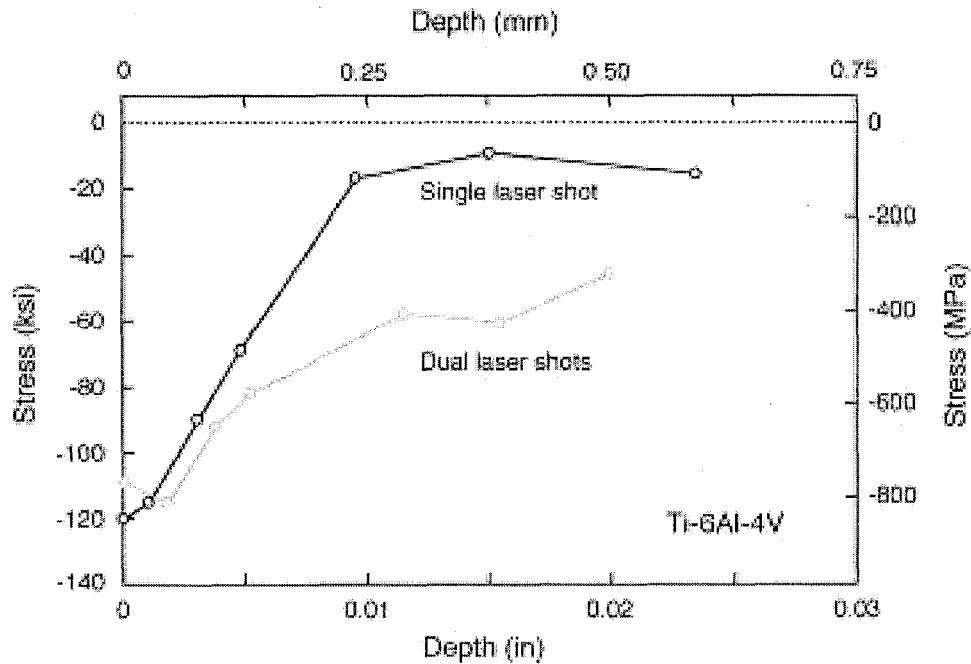
Figure 4. A first and then second laser shot pulse can generate successively deeper residual stress and thus larger stress volume in Ti-6Al-4V alloy.
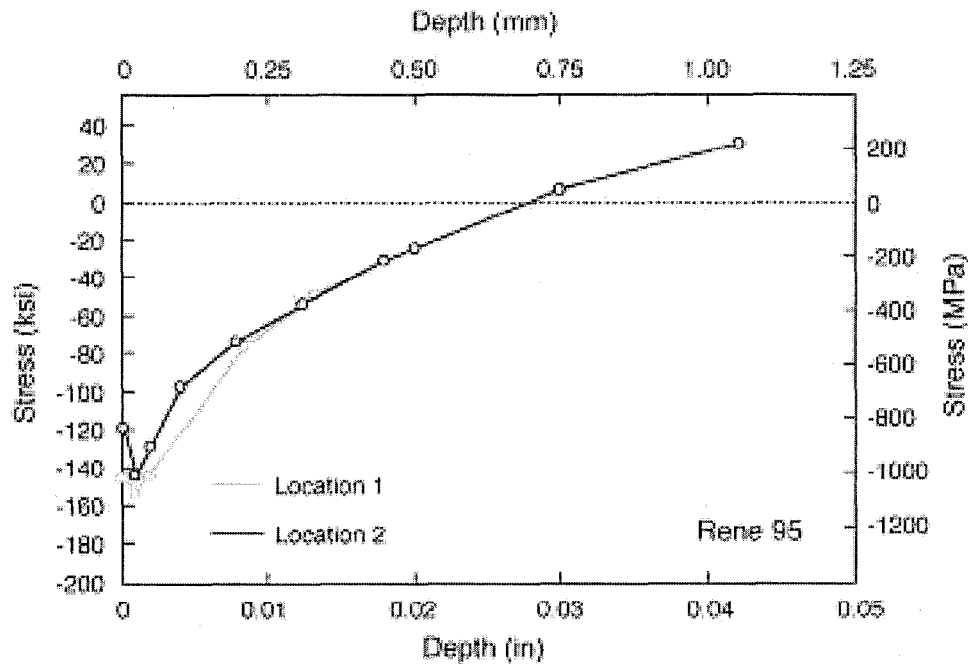
Figure 5. Compressive stress extending to depths of 0.75mm is achieved with single shots of the laser peening system in Rene 95, a nickel based super alloy with excellent heat resistance.

2.3. Laser Driver Requirements

In testing on operational components such as jet engine fan blades researchers have shown the laser treatment to be superior for strengthening new and previously damaged fan blades from fatigue and corrosion failure.[5] However the laser technology for doing these types of tests has been limited to producing pulses at less than once per second thus peening areas of about 1cm²/s. This rate is acceptable for laboratory demonstrations but is clearly not meaningful for cost-effective production.

Since the cost of any high pulse energy (100J) laser is dominated by the hardware required to achieve the single pulse energy, it is imperative to have high repetition rate capability (~10Hz) in order to minimize the production cost per laser shot.

Figure 6. Compressive stress extending to depths of 1mm is achieved with the laser peening system in Waspaloy, another important nickel based high temperature alloy.

3. HIGH POWER LASER TECHNOLOGY AT LLNL

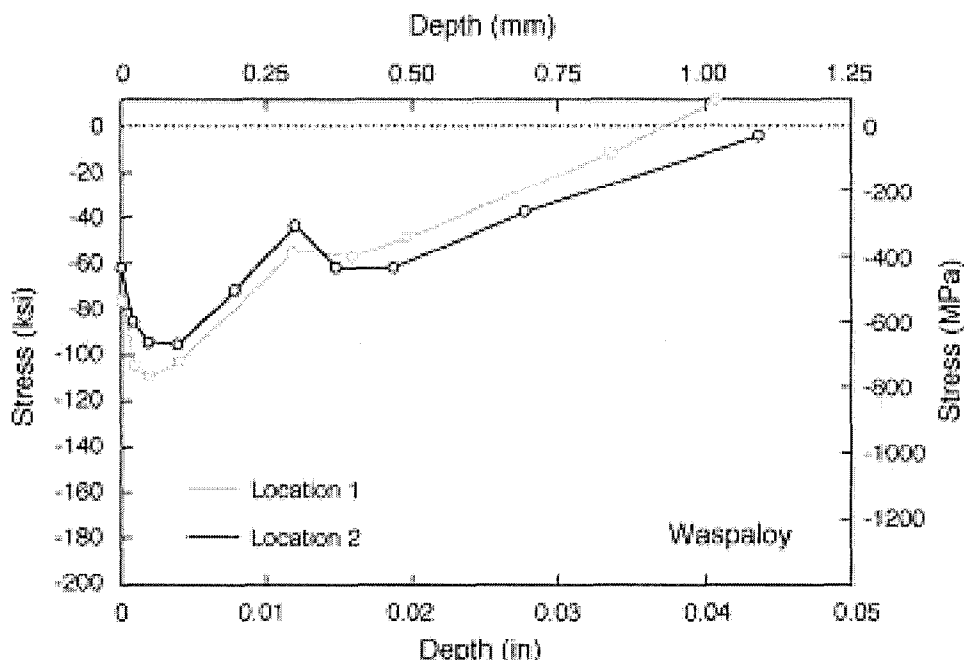The Laser Program at Lawrence Livermore National Laboratory (LLNL) has been a world leader in the development of high energy Nd:glass lasers for fusion applications for the past 25 years. The Nova laser, producing over 120kJ per pulse, routinely fires 6 to 8 shots per day for dedicated fusion and nuclear effects studies. More recently, the Laboratory has been directed by the Department of Energy to proceed with the construction of the National Ignition Facility (NIF) which will produce over 2MJ per pulse of energy at several shots per day. NIF is intended to reach ignition conditions where more fusion energy is generated than laser energy input. It is clear that enormous successful investment has been made to develop high energy solid state lasers.

Although generating high energy pulses from a solid state glass laser is well developed, generating high average power at high pulse energies has been problematic. Over the past decade, LLNL has developed higher average power systems with energies (depending on the application requirements) of 25 to 100J/pulse. This laser technology now demonstrates repetition rates of up to 10Hz and average powers near 1kW. The technology development has been supported by the Defense Advanced Research Projects Agency (DARPA) of the Department of Defense and more recently by the U.S. Navy and U.S. Air Force. The ARPA funding was focused on converting the infrared light to high average power x-rays with a wavelength of 10Å. This short wavelength has interest as a light source for proximity printing of advanced generation integrated circuits. The Navy and Air Force funding was directed toward obtaining light sources for long range and highly coherent illumination of missiles and space objects. One of our LLNL lasers went into service at a Navy facility at the Kennedy Space Center, Cape Canaveral, Florida and a second more power unit has been delivered to the Air Force Research Laboratory in Albuquerque, New Mexico. This technology has allowed us to develop a glass laser system with 100 J/pulse, adjustable pulse length from 10ns to 1μs, near diffraction-limited beam quality and an average power up to 600W. This laser technology is ideal for the laser peening application and exceeds the average power achievable by any commercially available laser technology by a factor of 20 to 50.

4. THE HIGH AVERAGE POWER ND:GLASS LASER SYSTEM

4.1. Design Strategies

A system suitable for laser peening must produce an energy in the range of 25 to 100J/pulse. The throughput of a peening system will then highly depend on the average pulse repetition rate that the laser can achieve. A laser system based on Neodymium doped glass (Nd:glass) gain media is the only identified technology that can realistically achieve this type of energy output at the required pulse duration. Such a system is typically based on an oscillator and one or more rod amplifiers which are optically pumped by flashlamps. As an unavoidable consequence of providing the optical gain, the flashlamps deposit heat into the glass. In steady-state, this heat must be removed at a rate equal with the rate of deposition, that is, at the pulse rate of the laser. Thus the glass must be cooled, typically by flowing water. As the glass is simultaneously heated and cooled, a thermal gradient develops from the center to edge of the glass. This gradient stresses the glass, inducing wavefront distortion and very significantly depolarization of the beam. Thus the thermal loading of the laser gain medium is a major limitation to the available average power that can be extracted from the laser. As the repetition rate of the laser is increased, the thermal loading correspondingly increases and degenerates the laser performance. This depolarizes and distorts the laser beam to the point of causing damage to optical components and preventing efficient optical extraction from the gain medium. In the limit, the thermal loading will fracture the glass. The LLNL laser design alleviates this thermal problem in three ways: 1) the slab gain medium is pumped in a highly uniform manner minimizing depolarization and distortion, 2) the laser beam is propagated through the slab in a zig-zag manner to average out much of the wavefront distortion[6] and 3) SBS phase conjugation completely corrects residual wavefront distortions.

4.2. Zig-Zag Slab Amplifier

The LLNL high average power Nd:glass laser technology is comprised of a single master oscillator and one or more power amplifiers. Detailed elements of the technology are described in references 8-12. The amplifier gain medium is the Nd-doped phosphate glass APG1 supplied by Schott Glass Technologies, Inc. or HAP4 supplied by Hoya Corporation. The glass is configured in a slab shape to provide one thin dimension for rapid heat removal. Typical slab dimensions are 1 x 14 x 40cm. The typical Nd doping level is $3\,10^{20}$ cm^{-3} or 2.7% by weight. Figure 7 shows a cross-sectional view of a flashlamp-pumped amplifier.
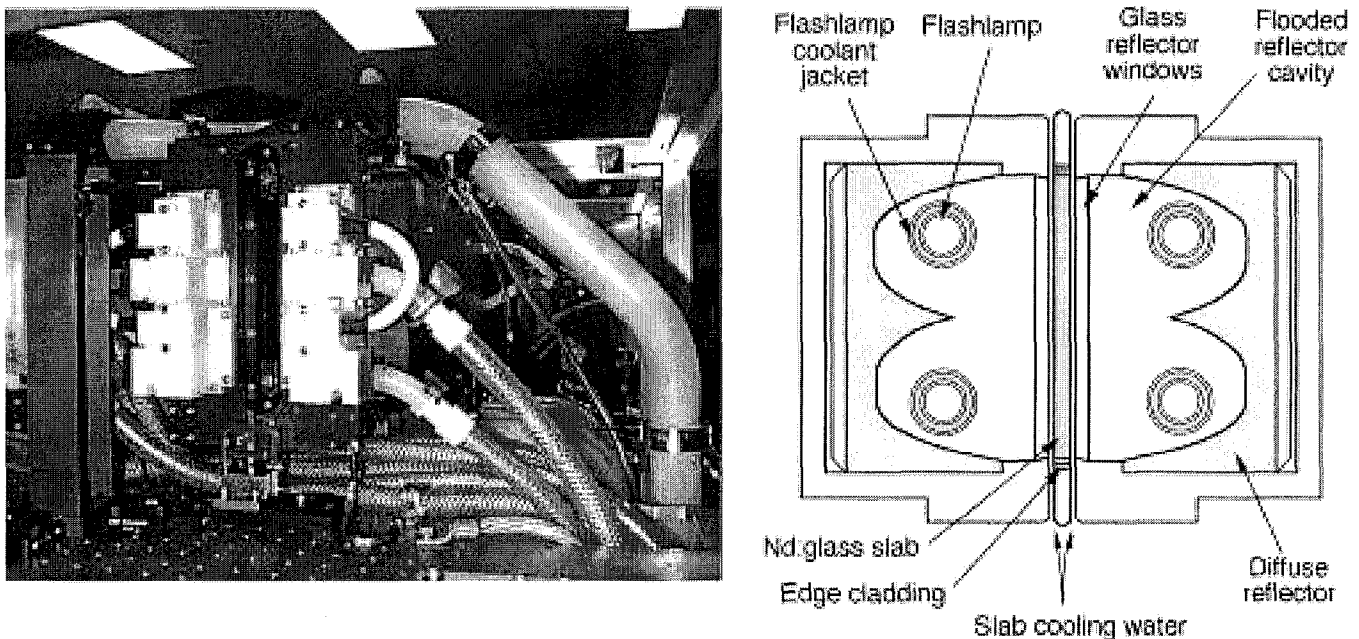

Figure 7. Photograph and cross-sectional view of the Nd:glass laser amplifier. Flashlamp light, tailored for highly uniform illumination by the diffurse reflectors, provides the excitation to the slab. The thin dimension of the slab provides efficient heat extraction into the water flow. The laser light zig-zags through the slab averaging the large horizontal temperature gradient.

Unlike a more traditional amplifier where the beam is propagated through the gain medium in a straight line, our design employs a zig-zag path, bouncing the beam internally off the slab faces by total internal reflection (TIR). As shown in the figure, the slab is positioned in the center of the assembly and has a narrow water cooling channel along both sides formed by the slab face and a reflector window. Two flashlamps on each side pump the slab through these cooling channels. A diffuse reflector surrounds the flashlamps and by appropriate shaping provides uniform optical pumping. The reflector is made of a high reflectivity diffuse reflecting material called Spectralon[tm] (produced by Labsphere Corporation) and is machined to a specific shape to tailor the pumping irradiance on the slab surfaces. Designing a thin dimension for the gain medium creates a short path for high heat conduction from the slab center to the cooling water. The resulting high heat transfer efficiency removes the heat buildup and directly increases the repetition rate capability of the laser. Very uniform optical pumping from the reflector assembly results in uniform energy distribution from top to bottom in the slab. At high repetition rates a large thermal gradient of as much as 50 C develops in the slab from center to edge. However, the laser light is directed through the slab so that the beam propagates in a side-to-side zig-zag path which averages thermally induced pathlength differences. This provides a high quality wavefront in the horizontal dimension even in the presence of this large thermal gradient.
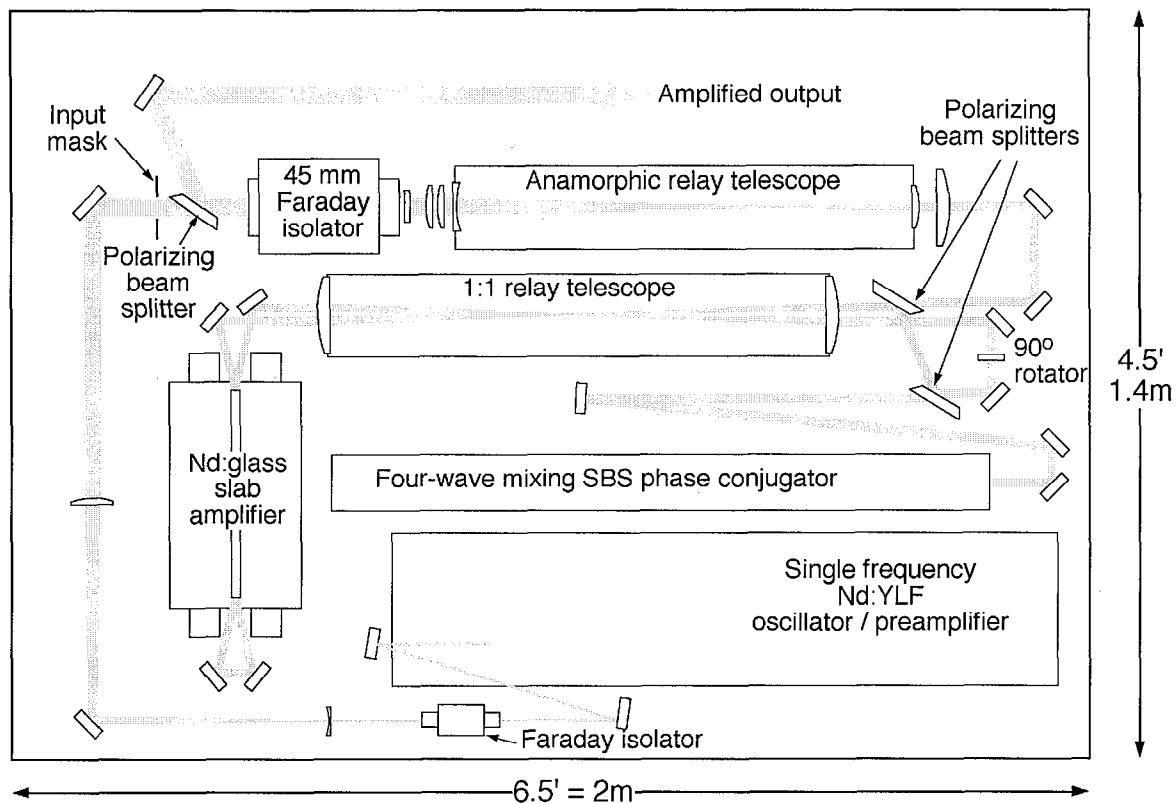

Figure 8. Typical layout of the high energy Nd:glass laser system with repetition rate of 6Hz. The high quality master oscillator output is amplified by 8 passes through the slab amplifier. The SBS phase conjugator provides necessary wavefront correction so that the output has near diffraction-limited beam quality.

4.3. Optical Architecture

A representative optical layout for the laser system is shown in Figure 8. The output of the oscillator transmits through a Faraday isolator and is then injected into the amplifier system through a polarizing beam splitter in p-polarization. The beam passes through the combination of a 45° Faraday rotator and 45° quartz rotator which are oriented so that the two rotation directions cancel in the injection direction. Still in p-polarization, the oscillator input transits through the first polarizer within the amplifier optical loop. After double-passing the Nd:glass amplifier, the beam polarization is rotated by a 90° quartz rotator and the now s-polarized beam reflects off the polarizing beam splitters, directing it to two more passes through the amplifier. The second pass through the 90° quartz rotator restores p-polarization allowing the beam to propagate to the

SBS phase conjugate mirror. Within the phase conjugator the beam generates an acoustic index grating by means of stimulated Brillouin scattering. This index grating acts as a special mirror, reflecting the beam back along its input path but with the phase of the wavefront inverted.[7] The beam retraces it path through the amplifier optical loop, accumulating four additional gain passes. In the final four amplifier passes, all of the wavefront errors accumulated in the first four amplifier passes are cancelled, generating a high power beam with near diffraction limited beam quality. On the way back through the Faraday/quartz rotator pair in the output direction, the two 45° rotations add, providing a net 90° rotation. This allows the now amplified output beam to reflect from the polarizing beam splitter in s-polarization and be directed through the beam formatting optics and onto the work piece. By correcting for thermal aberrations as well as manufacturing errors in the large aperture lenses and mirrors, our design allows us to extract average powers up to the thermal fracture limit of the gain medium. Without the phase conjugator the beam quality rapidly degrades as the laser average output power is increased. This degraded beam quality results in reduced focus control of the beam and less power on target. Of more importance, the reduced beam quality can lead to intensity "hot spots" within the laser and consequently optically induced damage. The SBS phase conjugator simply and reliably eliminates this problem. Figure 9 illustrates the beam quality of the laser with and without the use of a phase conjugator at 3Hz and a pulse energy of only 20J. This is an average power operating point that is less than half that achieved with SBS phase conjugation.

4.4. Benefits of SBS Phase Conjugation

There are additional significant advantages to the operation of the amplifier system with the SBS phase conjugator. Eight gain passes through the zig-zag slab amplifier can be achieved using passive polarization switching in the regenerative amplifier ring. The fact that the SBS cell provides interstage gain isolation makes this possible since, if it were replaced with a mirror, the small signal gain through eight consecutive gain passes would lead to parasitic oscillation from the small reflective losses of AR coated optical surfaces in the ring or in the output beam. A large aperture actively pulse Pockels cell capable of operating at the high average power densities in the amplifier optical loop is not required. The SBS phase conjugator also very effectively conjugates the first order aberration of tilt. This greatly reduces the sensitivity of the system performance to small changes of optical alignment in the loop. No change in output power or pointing direction during operation are observed for large mirror misalignments in the loop.
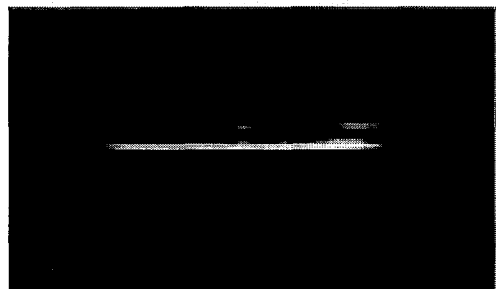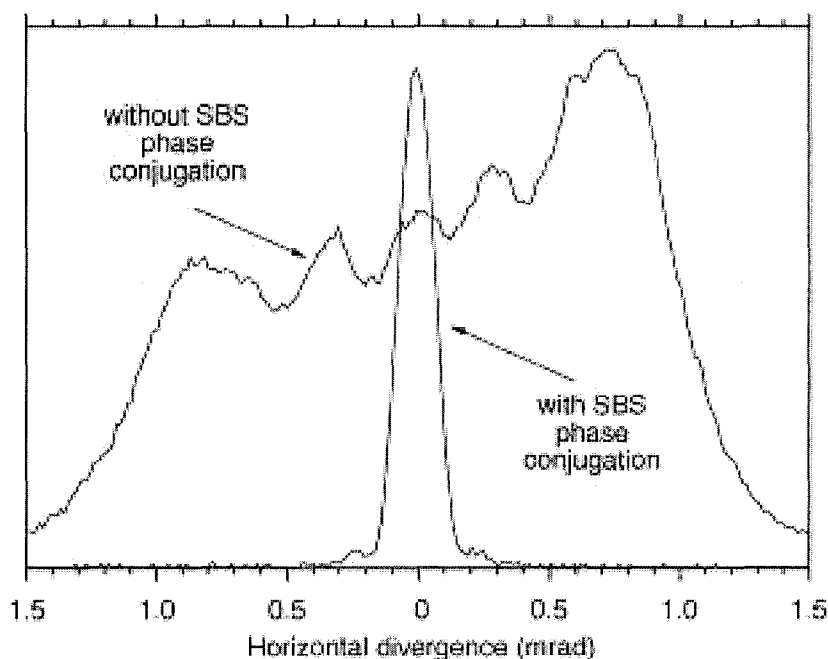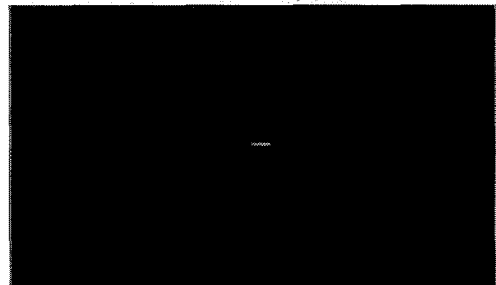
Figure 9. Comparison of laser operation with and without SBS phase conjugation at only 3Hz with an output energy of 20J.[8] With SBS phase conjugation, the average power can be increased another 2.5X beyond this level. The diffraction-limited far field profile has a 10:1 aspect ratio in this data due to the narrow near field profile of the slab extraction beam. The beam is anamorphically reshaped to a square for the laser peening application.

Finally and specifically for the laser shock peening application, the SBS phase conjugation naturally produces a fast rising edge laser pulse. Because the SBS is a nonlinear process with a definite threshold, the phase conjugator does not respond to the initial low intensity buildup typically associated with a laser pulse. The beam returned by the conjugator has its leading edge "clipped" and thus the returned pulse shape has a sharp, sub-nanosecond rising edge. This fast rising pulse is critically important for laser peening because it reduces the possibility of breakdown or other non-linear processes from occurring in the tamping material and prevents the premature removal of the absoprtion layer before ahead of the peak of the laser pulse. This allows a large pulse energy to reach the painted area on the metal and thus contributes to building the high intensity shock.

Although not presently needed for shock peening, the laser's high output beam quality enables efficient conversion of the infrared output light into green light. Conversion efficiencies for this laser technology range from 65% at 1µs duration pulses to over 80% for 10ns pulses. The use of the laser output doubled to 527nm could be useful for laser shot peening applications in the future that require long beam paths through water for certain *in situ* treatment schemes of underwater containment vessels. The green laser light does not suffer from absorption by the water at 1053nm.

4.5. Multiple Amplifier Pulse Energy Scaling

Achieving high output energy from a solid state laser is limited by the physical size of the gain medium, the saturation fluence of the material and the damage fluence that can be accommodated. Increasing the height of the slab becomes impractical due to the cost of large optics, particularly aspheric lenses and increases in length are limited by the control of amplified spontaneous emission. Increasing the thickness directly decreases the average power capability. However using our newly demonstrated technique of phase locking multiple apertures we can scale the laser output into greatly increased levels of energy and average power.[12] With this technique a single laser oscillator feeds multiple laser amplifiers and the beams are recombined into a single phase conjugator which effectively locks the separate channels into a single coherent laser beam. The far field beam quality is near the physical diffraction limit, the laser energy is that of the combined multiple apertures and the repetition rate is that associated with a single laser slab. Figure 1 shows the highly engineered 100J/pulse glass slab laser system built and packaged by LLNL. It is presently in operation at the U.S. Air Force Research Laboratory in Albuquerque, NM. This laser is being used in a long (500-600ns) pulse duration mode and frequency converted to 527nm for space object imaging. Its output energy of 100J/pulse at 10-30ns pulses with an average power capability of 600W offers an ideal source for laser shot peening.

5. ADVANCED FEATURES OF THE LASER PEENING SYSTEM

There is no commercially available laser peening system that can compare with the throughput capability, rectangular spatial profile and spatial beam control of the Lasershot[sm] Peening System. The high pulse repetition rate enables 10X greater system throughput than that provided by other available laser technologies and the rectangular beam profile enables more efficient part treatment coverage.

5.1. Average Power

The most significant feature of the laser peening system is the high repetition rate afforded by the laser. The lack of meaningful laser repetition rate has held back the laser peening technology from high throughput industrial introduction for many years. Now, the laser technology offered in our product enables for the first time acceptably high treatment area rates for industrial processing of components such as jet engine fan blades and rotors. Since the cost of a laser peening system is fundamentally driven by the hardware required to produce the necessary output energy, typically 100 J, the 10X advantage of our product's repetition rate will be translated to comparable increases in throughput per hour. With a nominally similar cost in capital investment, the higher repetition rate means a reduction in cost per part treated.

5.2. Beam Quality

Since laser shot peening is a "near field" optical process, it could be argued that output beam quality and beam divergence are not as important as they might be for a "far field" application requiring long distance free beam propagation. However, high beam quality operation is critical to the successful high average power operation of our laser driver. Competitive products do not control the wavefront in an active manner as is done in our system by the SBS phase conjugate mirror. Consequently, these systems are potentially close to optical damage limits when off-normal operation leads to increased thermal loading and consequent wavefront distortion. Wavefront distortion can lead directly to self-focusing which catastrophically destroys the

solid-state laser gain medium as well as high value optics. The SBS phase conjugator consists of a passive, inexpensive cell of liquid material which automatically maintains the high pulse energy wavefront near the physically allowable perfect limit. The conjugator, combined with an thermally efficient slab architecture, allows our system to run at 10X higher average power and throughput where other systems are limited by beam distortion and optical damage.

5.3. Temporal and Spatial Profile

Laser amplifier systems employing cylindrical rod designs naturally produce a round output beam spatial profile. Treatment of extended areas then requires overlapping spots in an inefficient manner. The naturally rectangular profile of the slab laser output beam allows full area coverage with each spot placed directly adjacent to the next.

Laser systems without SBS phase conjugation require rather elaborate hardware and techniques to achieve the sharp pulse rise times necessary for efficient shock production. These techniques involve exploding foils and/or fast switching, the latter requiring accurately timed Pockels cells that use high voltage pulsed supplies. The SBS wavefront correction naturally produces a sharp rising pulse without additional hardware.

5.4. Treatment Rates

The high average power available from the Nd:glass slab laser system enables for the first time a high throughput laser peening system. Assuming that 200J/cm2 is required to generate an effective 10kbar shock, the LLNL laser system, operating at 100 J per pulse and 6 Hz repetition rate, will have a throughput capability in excess of $10,000 \text{cm}^2$ per hour for single pulse applications and $5,000 \text{cm}^2$ for dual pulse applications. Upgrading the laser with the newly developed Schott Technologies high average power glass APG-2 and thus doubling its average power output, the throughputs could be increased to $20,000 \text{cm}^2$ per hour and $10,000 \text{cm}^2$ per hour, respectively.

6. SUMMARY

We have developed a class of laser system at the 100J/pulse level with average power capability approaching 1kW. Its new technology includes a uniformly pumped zig-zag slab gain medium, master oscillator/power amplifier (MOPA) architecture and phase conjugation to minimize the effects of thermal loading and correct the problems generated by it. This technology enables for the first time industrial application of a high throughput laser peening process.

ACKNOWLEDGMENTS

REFERENCES

1. B. P. Fairand and B. A. Wilcox, *J. Appl. Phys.* **43**, 3893 (1972).

2. A. H. Clauer, B. P. Fairand, and J. Holbrook, *J. Appl. Phys.* **50**, 1497 (1979).

3. P. Peyre and R. Fabbro, *Optical and Quantum Electronics* **27**, 1213-1229 (1995).

4. P. Prevey, D. Hombach, and P. Mason, "Thermal Residual Stress Relaxation and Distortion in Surface Enhanced Gas Turbine Engine Components," *Proceedings of ASM/TMS Materials Week*, September 15-18, 1997, Indianapolis, IN.

5. S. R. Mannava, W. D. Cowie, and A. E. McDaniel, "The Effects of Laser Shock Peening (LSP) on Airfoil FOD and High Cycle Fatigue", 1996 USAF Structural Integrity Program Conference, December, 1996.

6. W.S. Martin and J.P. Chernoch, U.S. Patent No. 3,633,126 (January, 1972)

7. B. Ya. Zel'dovich, N. F. Pilipetsky, and V. V. Shkunov, "Principles of Phase Conjugation," Springer Series in Optical Sciences, T. Thamir, Ed., New York: Springer Verlag, vol. 42, pp. 25-143, 1985.

8. C. B. Dane, L. E. Zapata, W. A. Neuman, M. A. Norton and L. A. Hackel, "Design and Operation of a 150 W Near Diffraction-Limited laser Amplifier with SBS Wavefront Correction," *IEEE Journal of Quantum Electronics* **31**, 148 (1995).

9. Lloyd A. Hackel and Clifford B. Dane, "High Power, High Beam Quality Regenerative Amplifier," U.S. Patent No. 5,239,408, August 24, 1993.

10. John L. Miller, Lloyd A. Hackel, Clifford B. Dane, and Luis E. Zapata, "High Power Regenerative Laser Amplifier," U.S. Patent No. 5,285,310, February 8, 1994.

11. Clifford B. Dane and Lloyd A. Hackel, "Long-Pulse-Width Narrow-Bandwidth Solid State Laser," U.S. Patent No. 5,689,363, November 18, 1997.

12. C. Brent Dane, J. Wintemute, B. Bhachu, and Lloyd Hackel, "Diffraction limited high average power phase-locking of four 30J beams from discrete Nd:glass zig-zag amplifiers," post-deadline paper CPD27, CLEO '97, May 22, 1997, Baltimore, MD.